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Possible origins of the spectrum of Fermi SNRs

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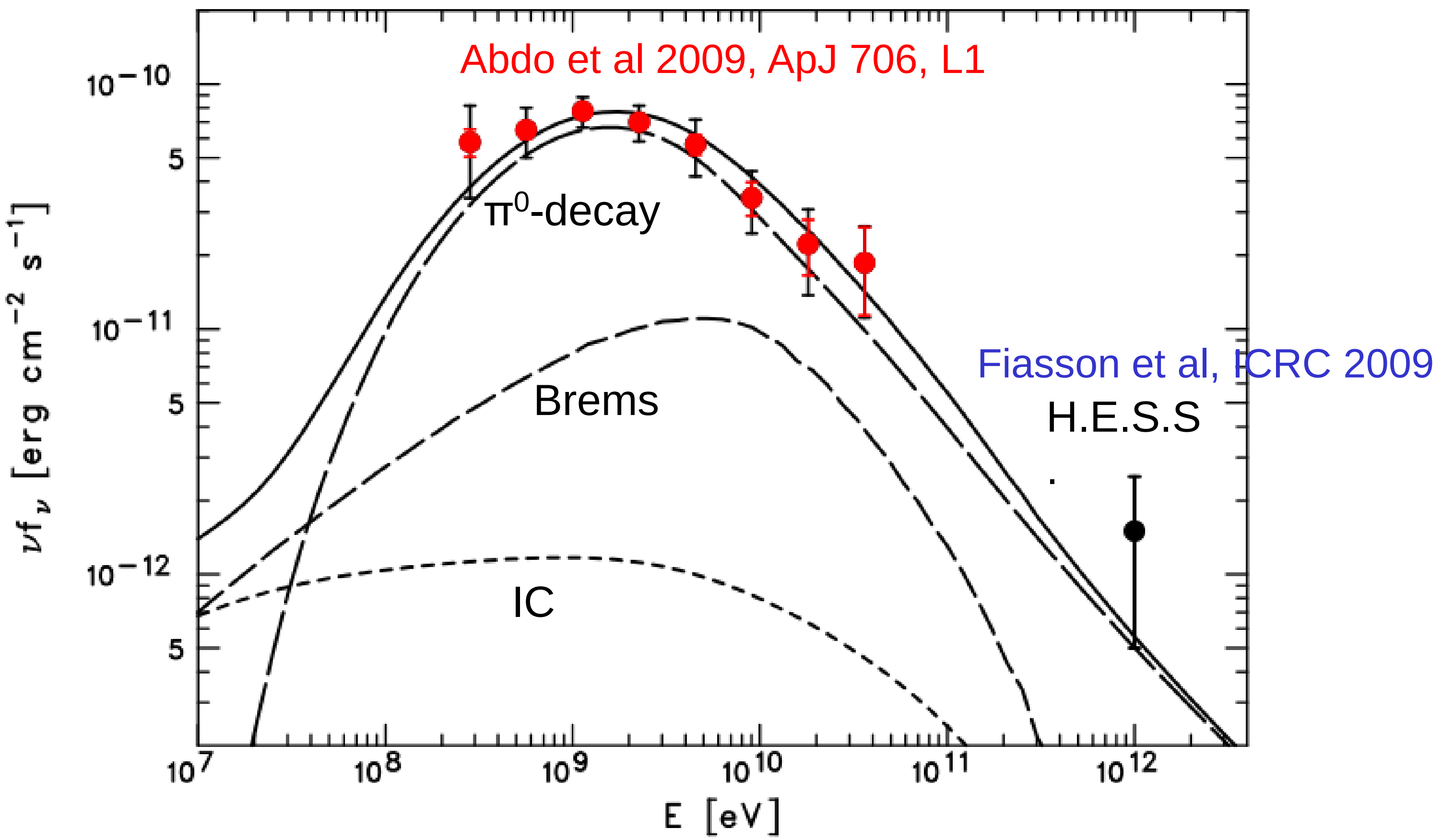
Context

HESS has observed several young supernova remnants with hard spectra below 1 TeV.

Fermi has observed several middle-aged supernova remnants with broken spectra, steep at 100 GeV

W 51 C

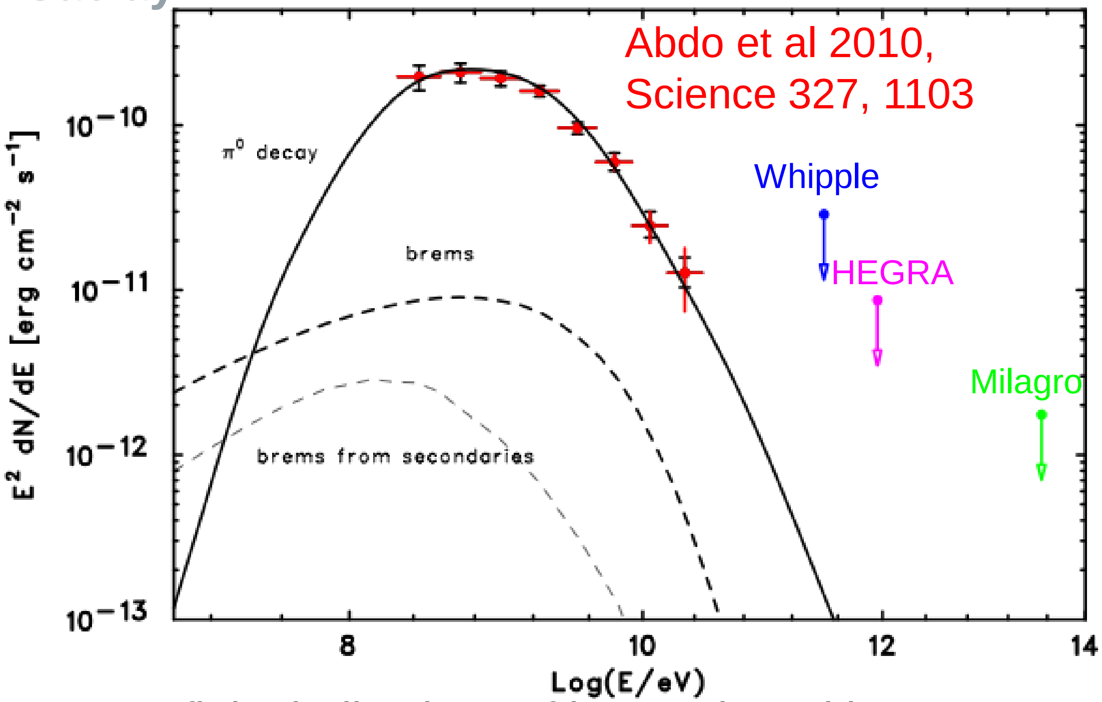
π^0-decay dominant case



One of the most luminous gamma-ray sources $L = 1 \times 10^{36}$ (D/6 kpc)^2 erg s^{-1}
Coincident with shocked CO clumps
Spectral steepening in the LAT range
π^0-decay model can reasonably explain the data, requires proton break at ~ 20 GeV

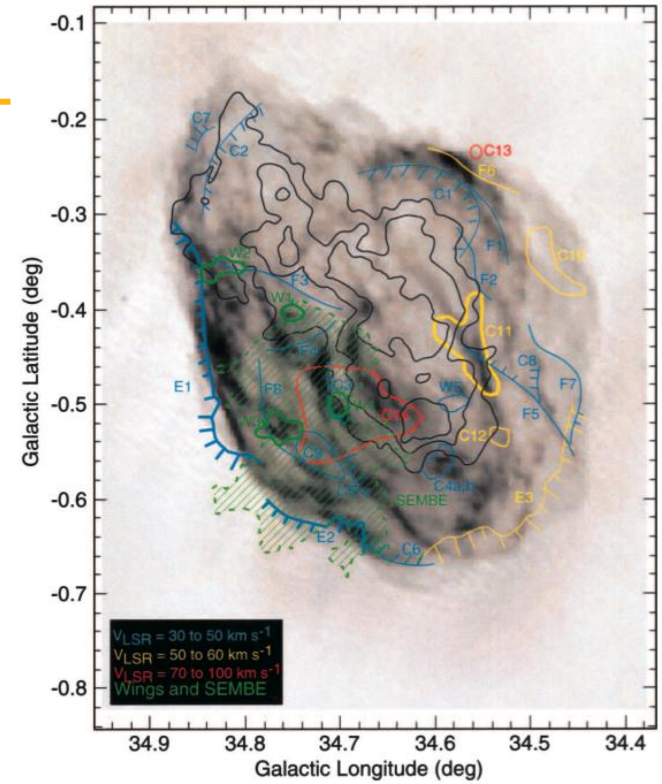
W 44

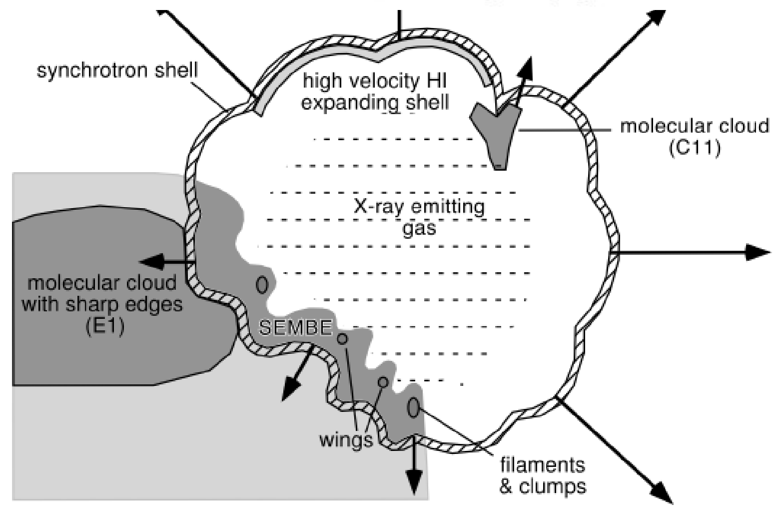
π^0-decay dominant case



Definite indications of interaction with a molecular cloud over a large fraction of the surface

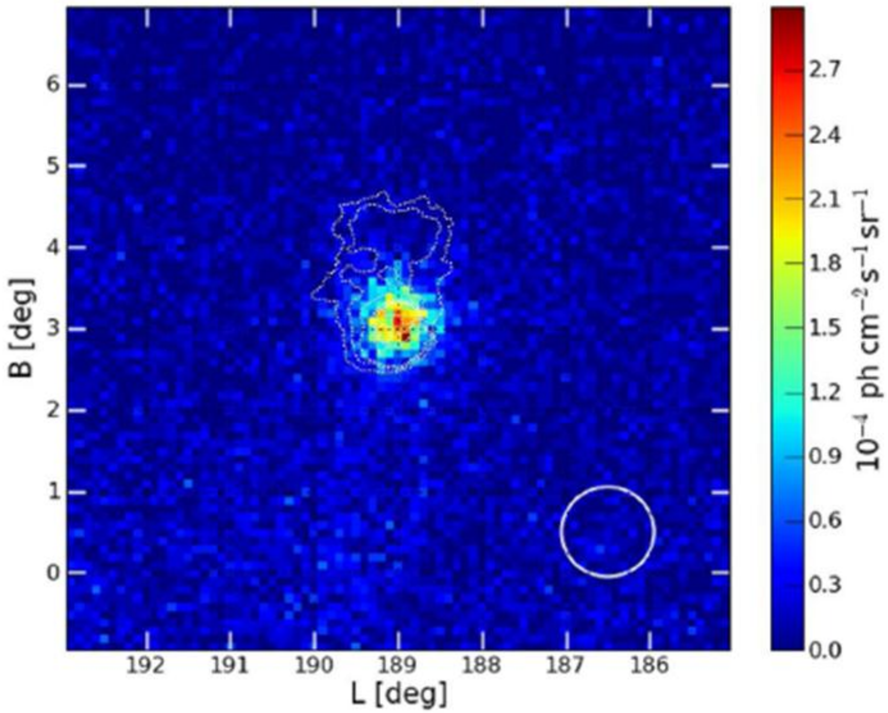
Protons need to have a spectral break at ~ 10 GeV

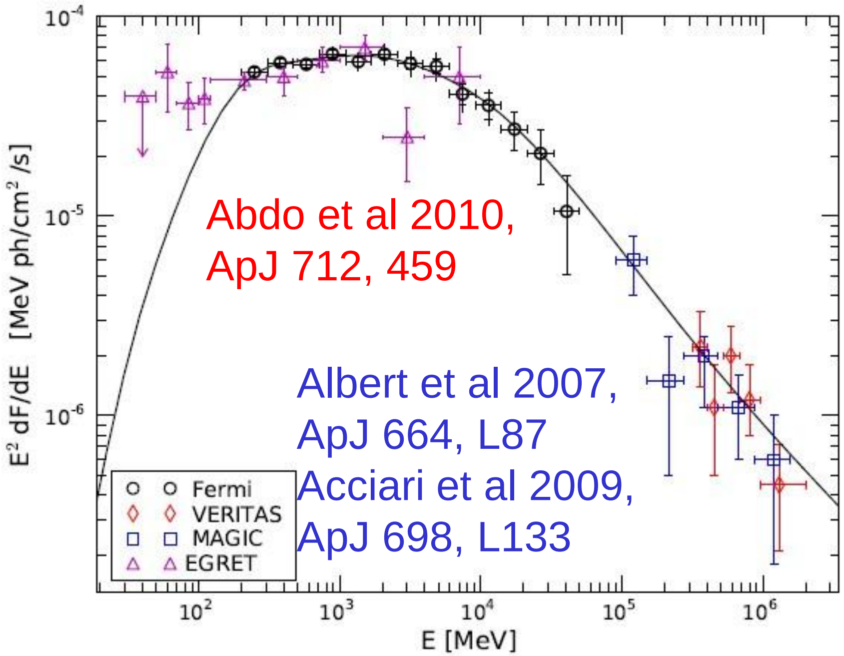




Seta et al. (2004)

IC 443





Emission where molecular clouds interact with the SNR, does not follow radio contours
Break frequency at ~ 3 GeV, corresponding to 20 GeV on proton spectrum

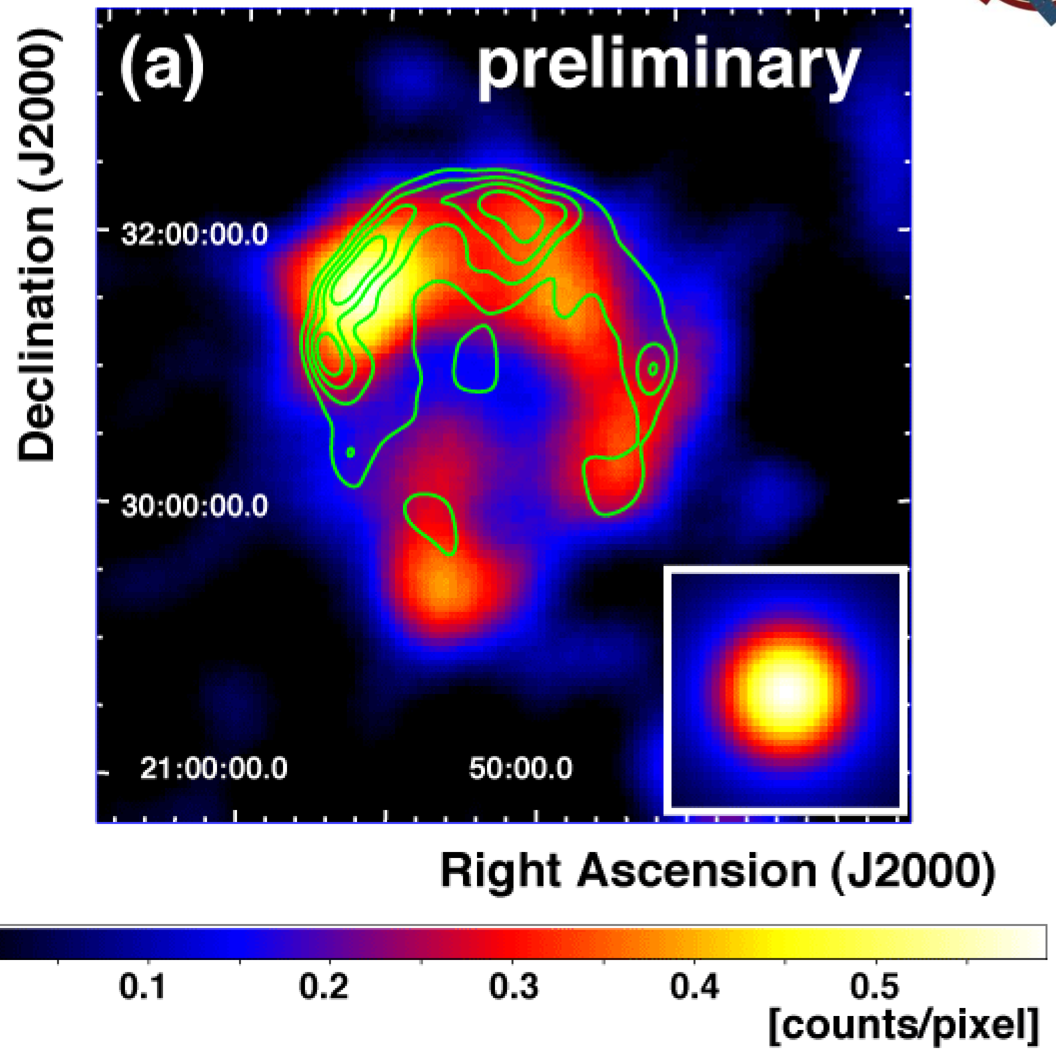
Also W 28 (Abdo et al 2010, ApJ 718, 348; Aharonian et al 2008, A&A 481, 401)
W 49 B (Abdo et al 2010, ApJ 722, 1303, no TeV)
3C 391, CTB 37 A, G349.7+0.2, G8.7-0.1 (Castro & Slane 2010, ApJ 717, 372)

Cygnus Loop

ROSAT X-ray contours overlaid.

No molecular cloud, only diffuse HI clouds.

Old nearby SNR, very large (3°)



Katagiri et al. 2010 for the LAT collaboration

Observational summary

Fermi has observed several middle-aged supernova remnants with broken spectra, steep at high energy but not exponentially decreasing.

Little doubt that this is hadronic emission from a region of enhanced CR density.

Most are quite faint at TeV energies.

They all seem to be interacting with (molecular) clouds.

This spectrum is not directly predicted by Diffusive Shock Acceleration models which predict a single (possibly concave) power-law up to an exponential cutoff.

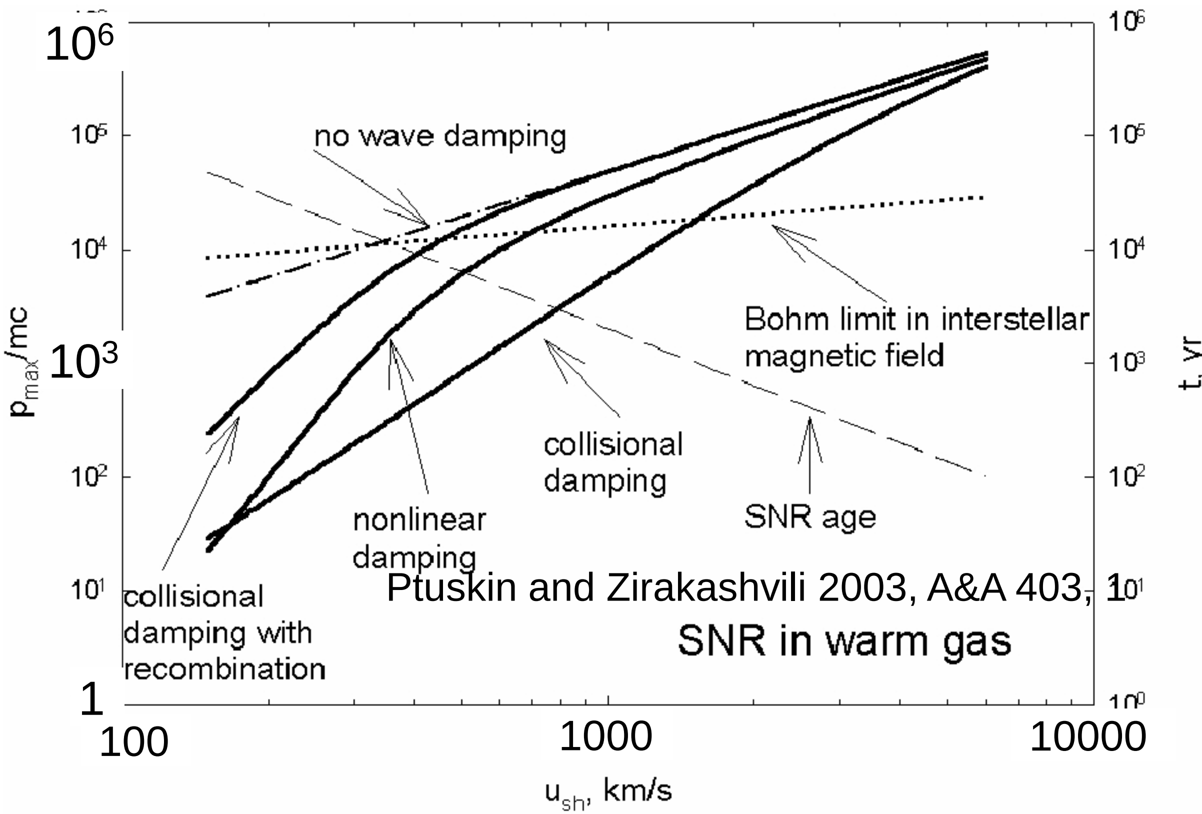
Key observable is break energy.

Several recent papers try to address that issue and understand what Fermi is seeing and what we can learn from it

Time evolution of magnetic turbulence

- ✓ The maximum energy of accelerated particles is limited by diffusion (turbulence level) because acceleration time increases with energy
- ✓ Some indication that B is lower in older remnants (broader synchrotron limbs)

- ✓ Excitation of the turbulence decreases with shock velocity, while damping (by non-linear wave interactions and ion-neutral collisions) does not
- ✓ Reduces maximum energy of particles
- ✓ Could allow already accelerated particles to escape



Diffusion effects

Ohira et al. 2010 for MNRAS, arXiv:1007.4869

SNR encountering molecular cloud

Assume enhanced turbulence at SNR shock dies off immediately, so that all CRs escape (E_{max} gets below 1 GeV) and diffuse in ISM (but allow diffusion as $D_{ISM} \alpha \chi p^{\delta}$ with free χ and δ)

Before that, assume maximum energy decreased as $R_{sh}^{-6.5}$ so that E_{max} reaches the knee at R_{Sedov} but decreases steeply thereafter

Simple spherical toy model with molecular cloud in the form of a shell surrounding SNR. Inner and outer radii fitted.

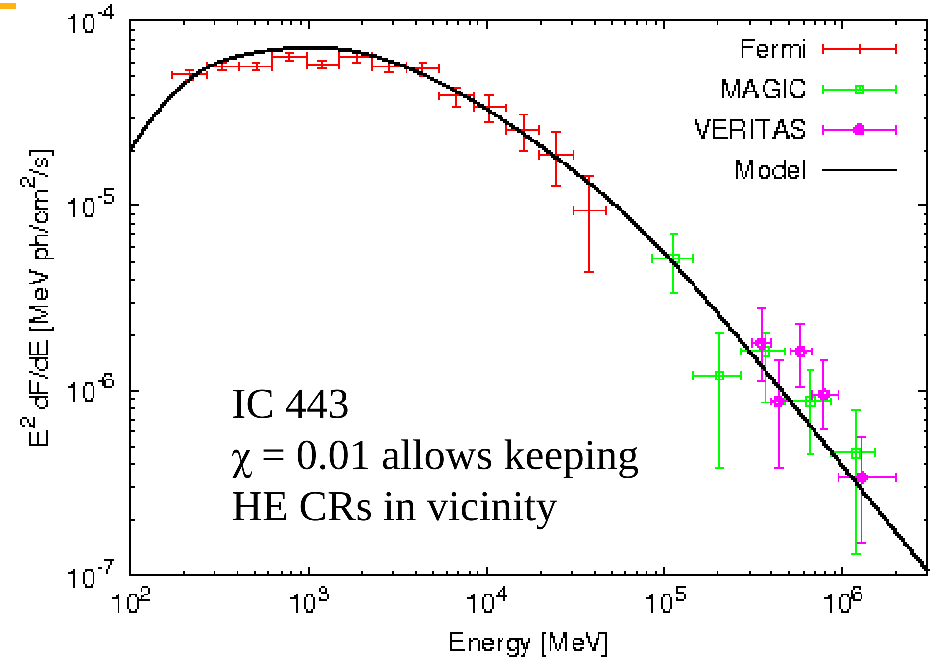
Main characteristic energy (break) is E_{max} at the time when the SNR reaches the cloud

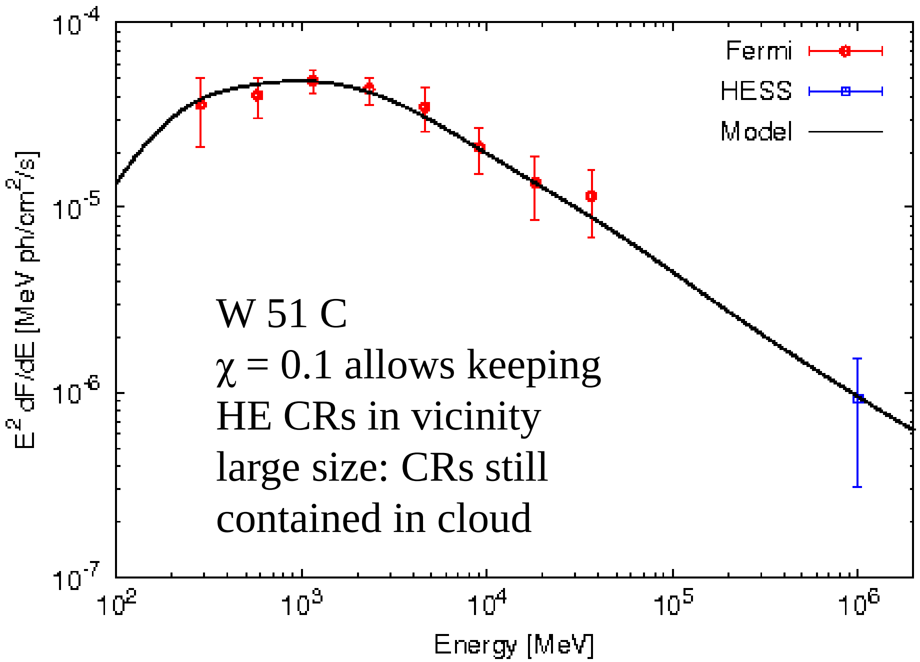
Diffusion effects 2

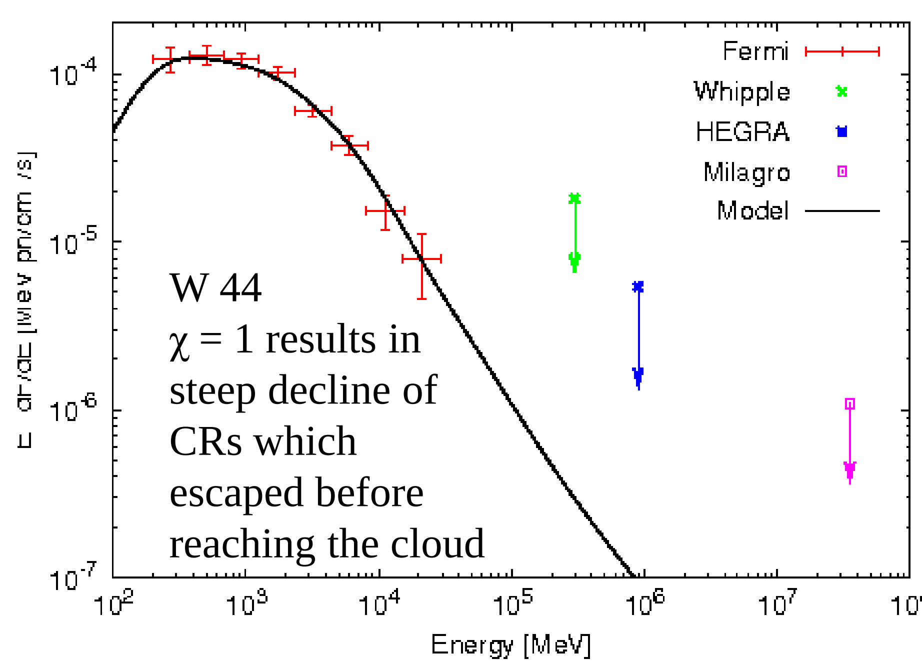
Can indeed reproduce the observed spectra but depends on geometric details (width of cloud in particular)

Requires more efficient diffusion outside W51C and IC443 (Ptuskin et al 2008, AdSpR 42, 486?), **also adjusted energy dependence**

Difference may rather be due to fraction of SNR surface impacting the cloud







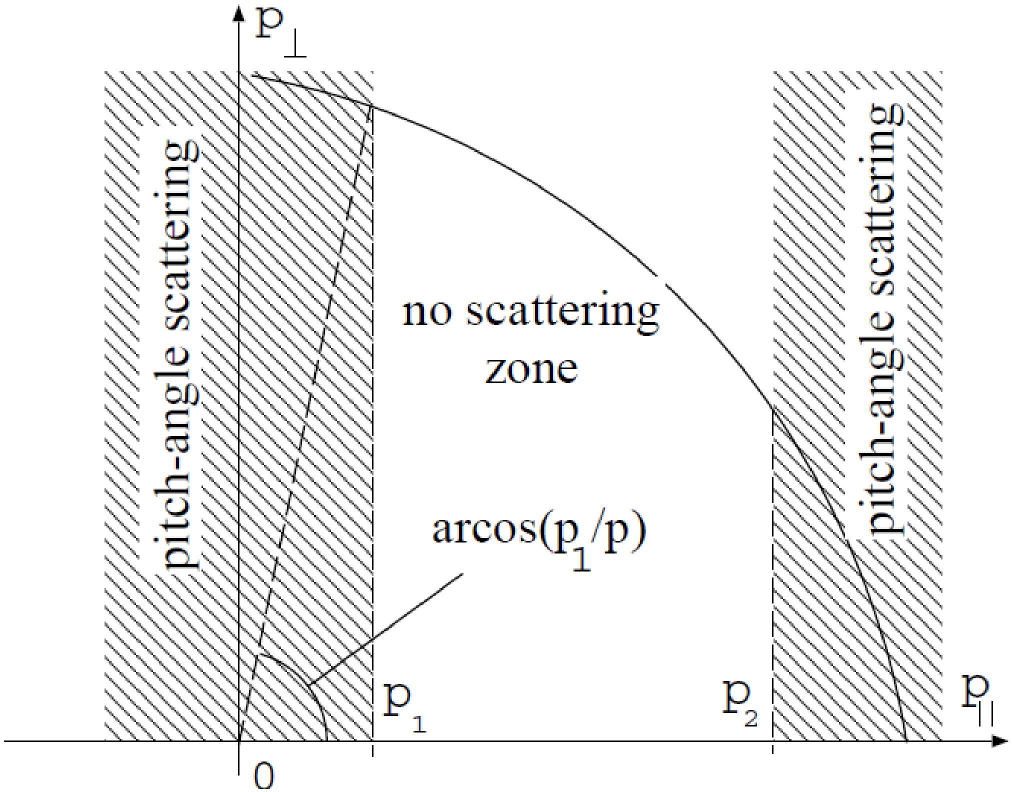
Effect of neutral medium

Malkov et al. 2010,
arXiv:1004.4714
not published yet

Damping of Alfven waves in mostly neutral medium ($\rho_i/\rho_0 < 0.1$)

Removes scattering above some momentum in parallel direction, allowing particles to escape

Pure geometric effect in momentum space, results for remaining particles in a slope steeper by 1 above the break at p_1



Only predicts a break in spectral slope by one unity

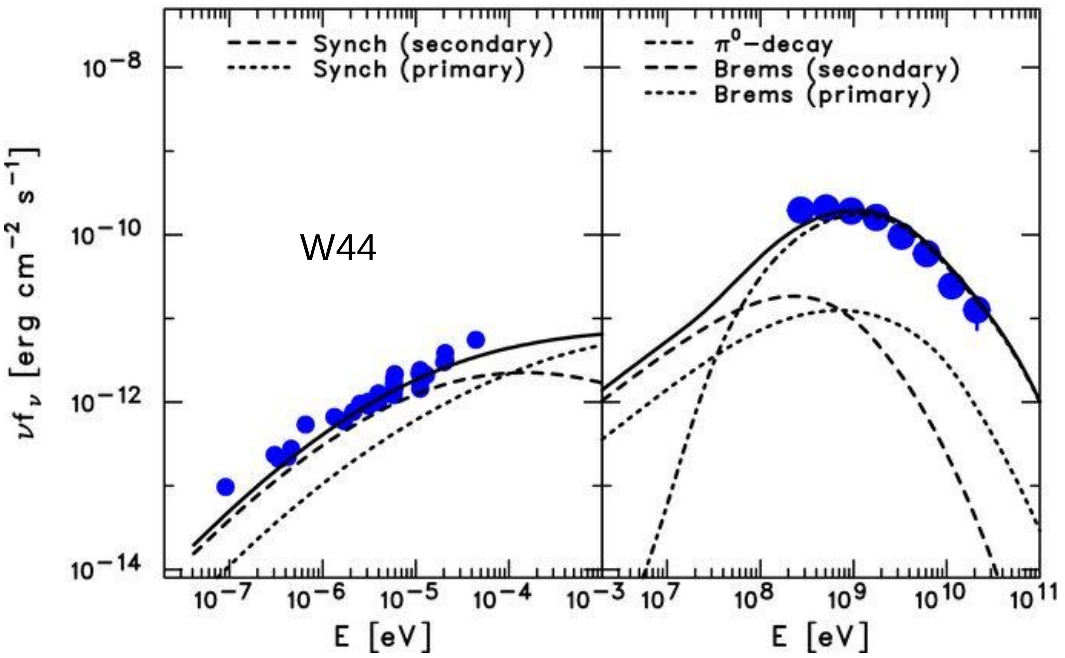
Fermi does not seem to see a universal break

Particles with $p_{//} < p_1$ but $p > p_1$ would escape anyway after a few scatterings?

Reacceleration of existing CRs

Uchiyama et al. 2010, ApJ 723, L122

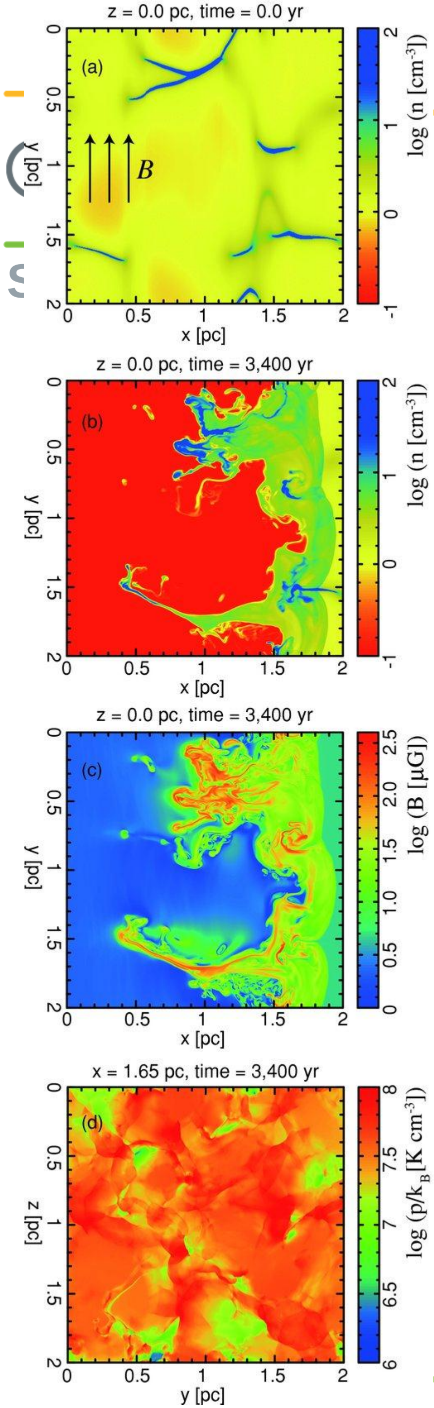
- Starts from normal Galactic CRs in molecular cloud (≥ 100 cm^{-3})
- Reacceleration (no injection of fresh particles) at slow (50 - 100 km/s) shock
- Additional adiabatic compression by factor ≥ 10 due to cooling behind the shock, limited by magnetic pressure
- That compression increases both the gas density (up to 10^4 cm^{-3} and that of accelerated particles, leading to a very efficient mechanism
- Cannot explain TeV emission (low v_{sh} means low E_{max})



Very clever idea. Luminosity reasonable (10^{35} erg/s). Details needs to be worked out

Emission comes only from shocked regions in that case, not from nearby unshocked material

Not much to do with origin of Galactic CRs



Secondary shocks

Inoue et al. 2010,
ApJ 723, L108

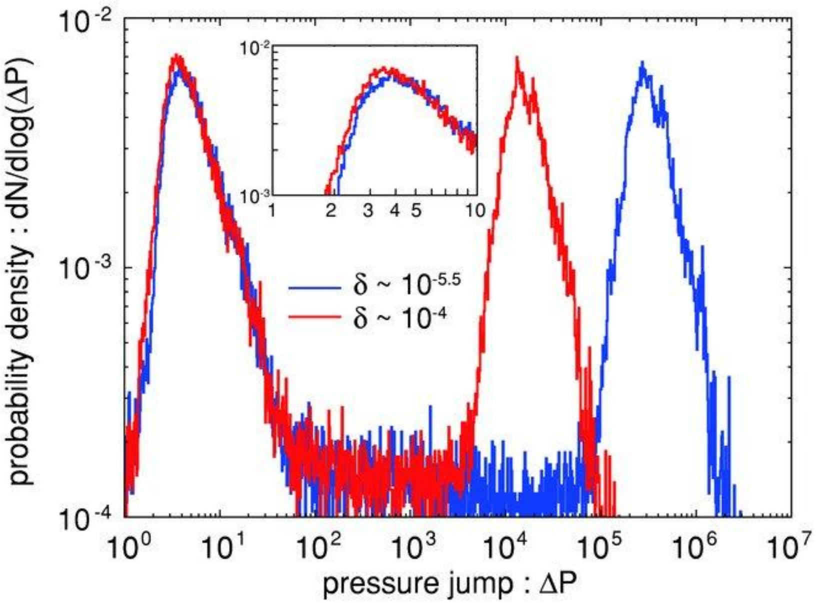
SNR propagation in turbulent cloudy ISM

SNR shock overtakes the clouds

Weak (Mach $\approx$ 2) reflected shocks in front of clouds

Particles can be reaccelerated in those shocks. Low Mach means steep spectrum

Can explain the power-law at high E if incoming spectrum is exponentially cutoff, with $3 < \Gamma < 4$ according to Mach number



Main difficulty: secondary shocks act on gas coming from inside the SNR, shocked very early on, not the recently shocked gas with low maximum energy of accelerated particles

Summary

The fact that the shock moves into a neutral medium is probably the reason for the steep spectra

The spectrum can be explained by sudden escape of CRs as the shock reached the cloud and propagation effects.

Many geometric issues.

Could also be due to reacceleration of existing CRs in the slow shock, followed by compression due to cooling.

More directly testable, but cannot explain TeV.